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Interim Progress Report

NASA CR-53881

Contract NASr-14

September 1, 1963 - November 30, 1963

Experiments on optical testing have resulted in a paper "A Compact Radial Shearing Interferometer Based on the Law of Refraction" by Professor M.V.R.K. Murty which has been accepted for publication in APPLIED OPTICS and will appear sometime in 1964. Reprints will be submitted to NASA when available.

Other work now in progress includes:

1. The design study of a light weight mirror having rapid thermal response, uniform face plate support, and uniform thermal conductivity from the three points of support to the face plate.

2. Design study of a concept which might lead to a light weight mirror that could deform under loading without change of figure.

3. Experimental study of glass moulding techniques for complex, light weight structures.

4. Optical observations of mirrors on a shake table to reveal dynamic deformations.

A report is attached on "The Grind-Milling of Light Weight Mirrors of Glass", by N. A. Hochgraf.

RC #1

The Grind-Milling of Light Weight Mirrors of Glass

by N. Hochgraf

Contract NASr-14

Abstract

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A method is described for grinding out pockets in a solid block of glass to produce a light weight ribbed structure which might be used as a mirror blank. Author

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Introduction

Light-weight mirrors are important for astronomical instruments because they might make possible a substantial reduction in the weight and complexity of the mirror cell. This might allow a reduction in the weight of the main tube, of the counterweight, of the bearings, etc.

The same reasoning applies with even greater force for space applications. An orbiting telescope or even a balloon-borne telescope benefits many-fold from a reduction in the weight of the primary mirror.

Weight alone is not the only consideration. Mirrors deform when undergoing a change in temperature, and heavy mirrors are sluggish in response to temperature changes. Light mirrors might be designed to respond more rapidly.

The actual design of a light mirror is a complex problem which we do not yet understand completely. In particular, we cannot readily identify the principal stresses which the mirror must deal with. Terrestrial telescope mirrors sag appreciably under their own weight to conform to the constraints of the support, and elaborate support systems are commonly used. A complete system design calls for optimizing the mirror and cell together. A light mirror which demanded a more elaborate support might in practice give no net benefit. What is needed, then, is a favorable "strength-to-weight" ratio in the mirror so that the cell, too, can be light and simple.

In the space environment, the mirror is weightless, and doesn't droop even with a simple, three-point support. It then needs to be only rigid enough to be made and tested on the surface of the earth where quite complex supports might be used. The design of the

mirror can be essentially separated from the cell design, then. Of course, the mirror needs to be strong enough to survive the vibrations of launch, or to be cushioned to protect it from the vibration.

This diversity of conditions makes it very difficult to pin down a particular consideration and optimize for it. We need to accumulate experience with mirror blanks differing from present designs in various ways and see what problems turn out to limit the performance. We are engaged at Rochester in such studies. One of the various possibilities is the subject of this report.

Rib or Box Structures

The stiffness of any structure will be improved if its second area moment of inertia is increased, and if weight is important, the moment should be increased by increasing the radius of gyration rather than the mass. This demands a ribbed or box structure with lots of empty space. The number, direction, and symmetry of the needed ribs or pockets will depend upon the distribution of the forces that are to be resisted, but this we don't know for sure. It seems clear, however, that there is a common need for such ribbed or built-up structures in all the applications for light-weight mirrors and since we want the theory and the experiments to proceed together, we have carried out the study described here.

Hogging-out Versus Building-up

Ribbed or box structures can be made by fusing or sagging from thin sections, by casting, or by cutting holes in solid pieces. All these methods hold great promise, but this particular study was concerned with the cutting out of pockets in a solid piece of glass.

Glass was chosen for the material of this study because it is homogeneous, hard, isotropic, and elastic. Its principal defect is its low thermal conductivity. Glass has two very important properties which make it valuable as a mirror material. The first is brittleness. It either recovers from a stress or breaks, but does not ordinarily deform. Second, glass can be visually examined for homogeneity and strain nondestructively as it was in this study. Quartz could be substituted for glass.

Two principal reasons made this technique attractive to use.

1. We could minimize the problem of joints.

2. We could cut ribs or pockets with fillets where the ribs meet the face plate.

Filleting is accepted by engineers as a method to ease the flow of forces around structural intersections. Extensive tables (though unfortunately not directly applicable to this particular study) are available in engineering text books. These show both the importance of and the magnitude of typical stress concentrations under various loadings. They show, for instance, that a right-angle corner will give a stress concentration of about three. This means that a stress applied to a body having right-angle joints may exceed the elastic limit or even the breaking strength locally and produce a permanent deformation or fracture even if it is only one-third of the elastic limit in other parts of the body. By rounding-out the material at the joints with a small fillet, the stress concentration is substantially reduced and the body is much less likely to show hysteresis or other failure. Such a bead or fillet is quite common in welded structures, but very difficult to introduce into a fused structure. We have shown

in this study that it is possible to grind out thin-walled pockets in glass and leave a fillet. The weight penalty is only about 7% while the potential benefit in strength-to-weight ratio is appreciable.

It must be made clear again that although the strength-to-weight ratio is quite clearly what is important, it is doubtful if any mirror has ever been made so delicate and fragile that its design can be said to be optimized. In particular, we don't know what stress is the most hazardous, and thus we don't know clearly what strength is needed. This study was then aimed at the development of a technique, rather than the building of a particular mirror.

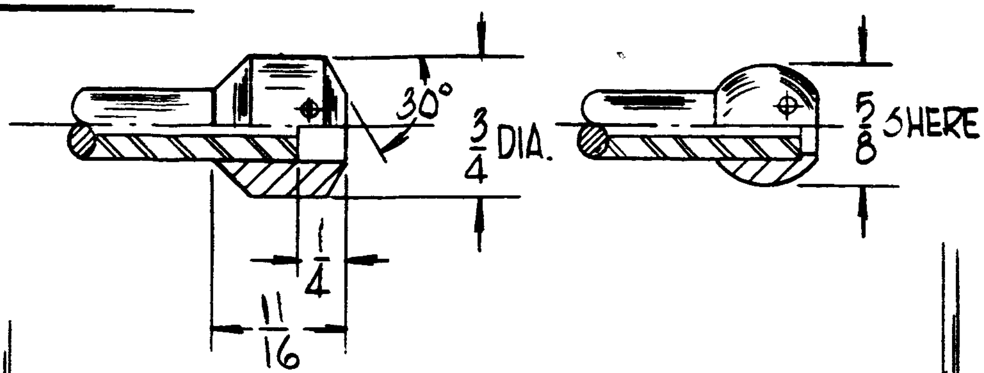
The Grinding Technique

We call the technique we have developed "grind-milling." The material is removed by diamond grinding, but the tool is moved as it is in a milling machine, cutting sometimes with the end and sometimes with the side.

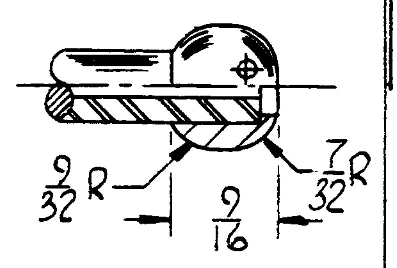
For simple ribs, the tool might have been made with a simple cylindrical shape, but we wanted to undercut the ribs so they would be thikker at the free edge, so we designed a tool with a thin shank and a ball-like cutting head. See Drawing SK-56.

This has an additional advantage. The tool is rather flimsy with a well relieved shank so that it will tend to yield and not the glass if the cutting forces become high. The cutting head is 5/8" diameter and the tool has a long reach and shank relief.

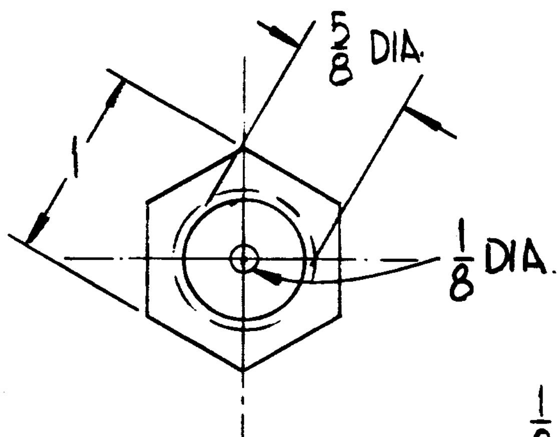
Milling needs sharp diamonds firmly held in the tool metal matrix, operating at low loads, flushed constantly with coolant, and operated at a nominal surface speed of between 3500 to 5500 surface feet per minute.

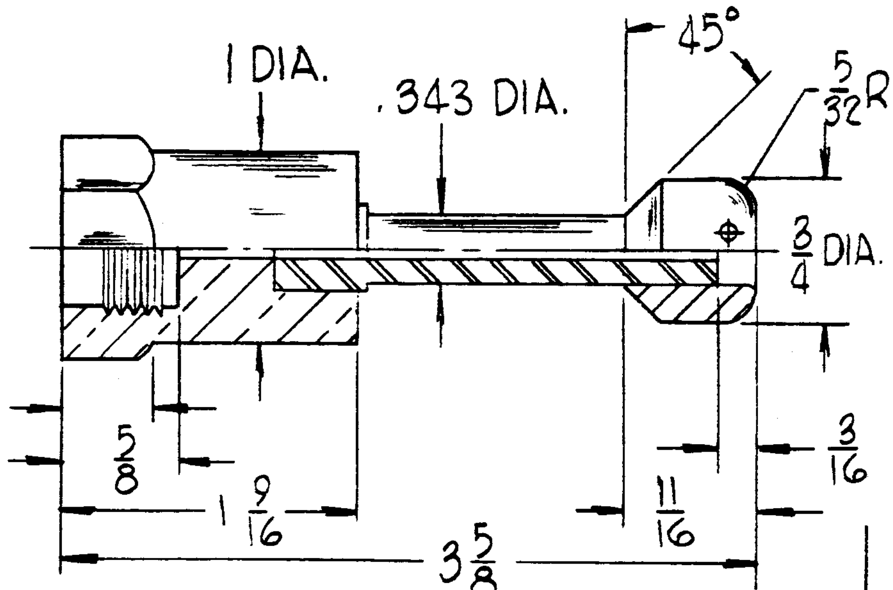


DIAMOND TOOL BEFORE USE

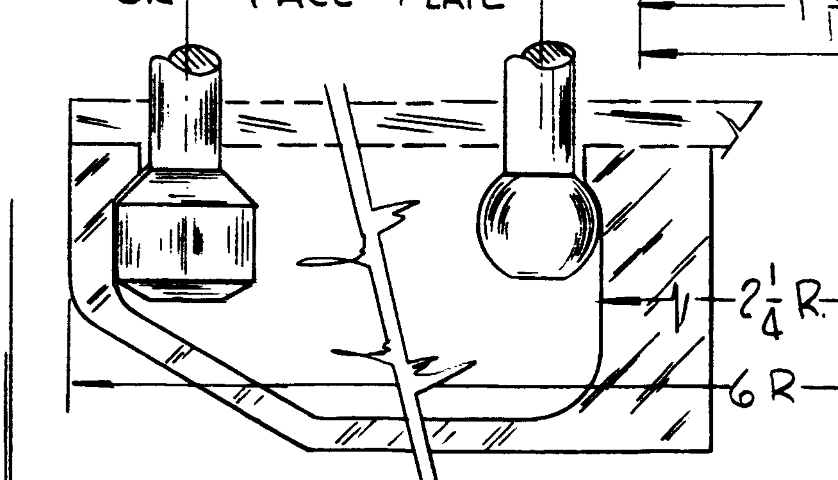


DIAMOND TOOL SHAPE AFTER REMOVAL OF 18 CU.IN. OF PYREX





POSITION OF FUSED ON FACE PLATE



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When a situation is encountered, even for several revolutions of the cutter, where the load and rate of glass cutting are too high or lubrication is insufficient, the surface diamonds of the tool are mechanically loosened or thermally fractured. A new and satisfactory cutting surface may be reestablished by wear of the metal matrix within a short time and maintained by proper operating conditions. The harm lies in the reduction of the tool diameter, which changes the cutting geometry. There is also a reduction of tool life.

Because the diamond may rather quickly recover its sharpness as the metal matrix wears down to new sharp diamonds, the condition of cutting tends to become oscillatory with regard to minor misadventures. This condition is exaggerated by the small diameter and long springy length of the diamond tool shank. Caution is needed to avoid dangerous hogging into corners and other unusually rapidly increasing load conditions. Such hogging actions are indicated in the photographs of strain polarization at some of the exessively undercut pocket corners. Control of feed is very important.

A diamond is very brittle and cannot be used with a large cutting force. To have appreciable rates of work and light forces, one must go to very high surface speeds. With a small diameter tool, this means very high rotational rates, 10,800 rpm in our case. This gives a surface speed of about 1700 ft per minute. With this speed, we can move the tool about 20 inches per minute cutting 0.010 to 0.020 inches depth, but no more. This can give a useful volume of about 0.9 cubic inches per hour of milling.

The region being cut must be well lubricated with coolant.

The speed of the stroke (.3 inches per second) and the confusion of water make it hard to see what is happening, and the low amount of energy dissipated in the work (compared to the total required to overcome friction) makes it hard to tell by the feel of the machine. Thus there is a considerable requirement for machine reliability and if possible machine feel must be heightened. The sound of the cutting is a useful clue to the behavior of the tool. In an automated process where a pre-planned program would be followed, a suitable set of checks would be to measure the strain on the diamond probe, and the speed of the tool.

Apparatus

The glass grinding-milling machine picture in Fig. III is a radial-arm wood saw modified to stroke radially in the control of a mechanical template. Power for the grinding is provided by a $1\frac{1}{2}$ hp motor and transferred to the grinding spindle by a heavy-duty flexible shaft operating at 3600 rpm in an inverted "U", 6' long, and terminating in a 1:3 spur gear box. The shaft speed is then 10,800 rpm, which is somewhat slow but suitable for a diamond ball cutter of $\frac{1}{2}$" diameter.

The spindle uses a stainless steel shaft with widely spaced, high precision stainless bearings (open) cooled by side-injected filtered water. Water is also axially fed to the tool (See Fig. IV) down the shaft. Axially flowed water going in the other direction also cools and lubricates the gears. Variations in water pressure and cleanliness have been the chief difficulty of this arrangement. Since the instrument was originally to be a first trial machine the spindle barrel was made of brass and the thermal problems proved initially somewhat annoying.

The whole concept of a remotely driven spindle was undertaken

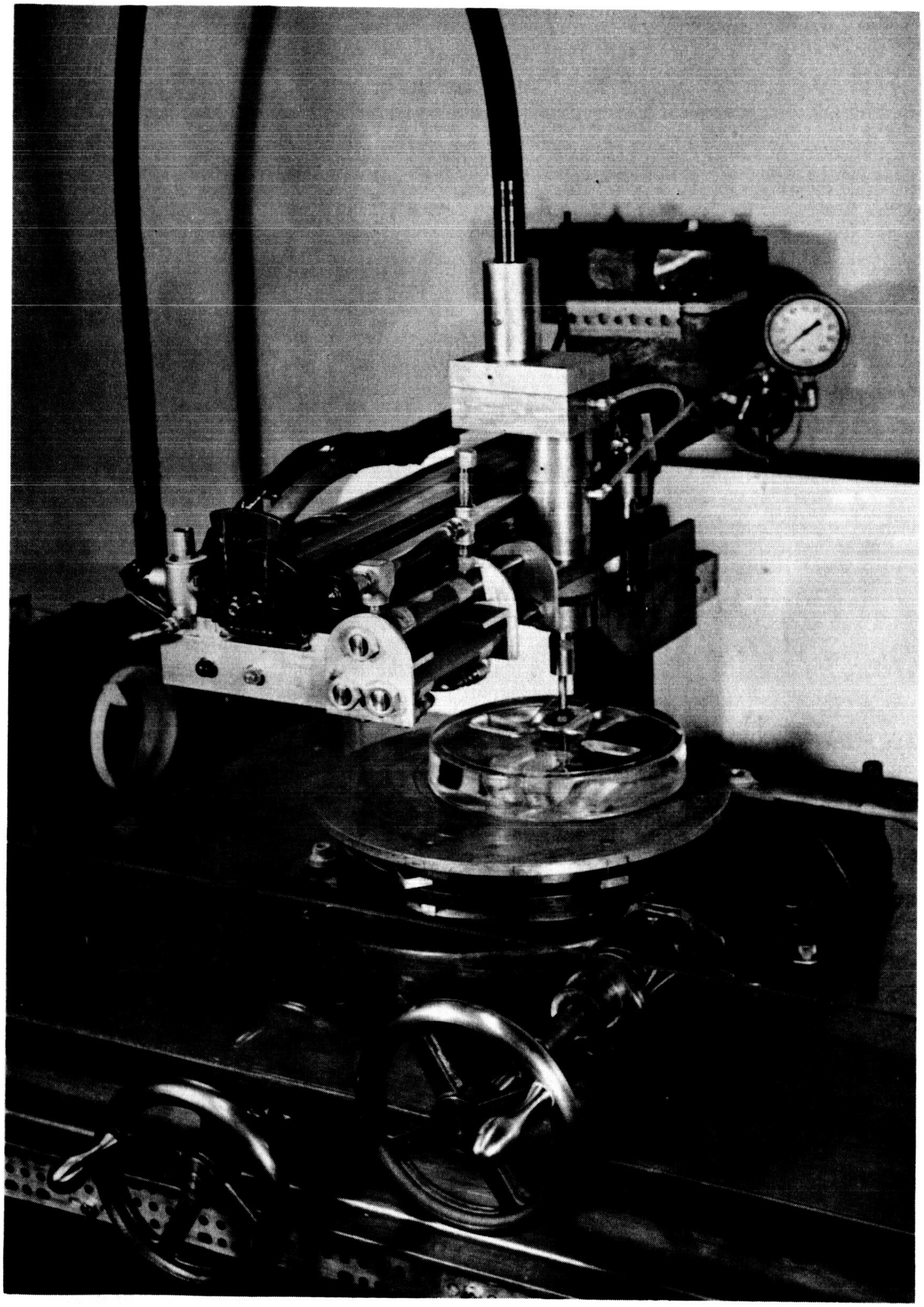

Fig. III. The Machine

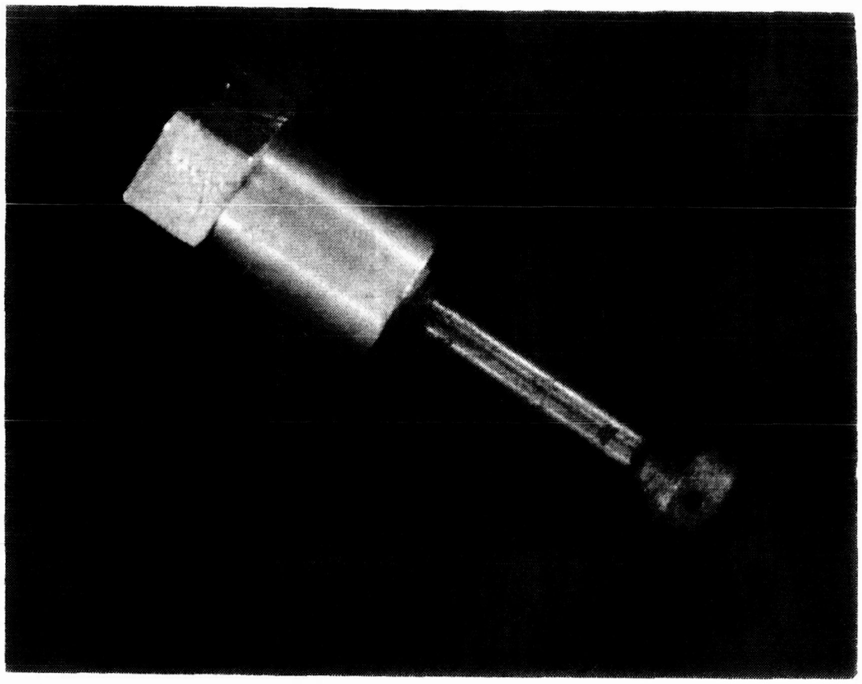

Fig. IV. Typical Diamond Roughing Tool after Considerable Use.

Overall length is approximately 5 inches

in order to reduce the moving mass and avoid the possibility of shock hazard in the misty, wet environment. In fact, as it was built, the weight of the spindle and half of the flexible shaft perhaps exceeds the weight of a high speed grinder motor. Certainly the use of an electric motor directly would probably cut the power requirement to a third, but would make direct axial feed of the coolant difficult. While it seems attractive to apply a solid stream of water, a fog of water droplets might in reality provide sufficient cooling and reduce hydraulic forces and the needed power. The centrifugal forces of feeding the water radially to the shaft axis made a booster pump necessary.

Results

No mirror has been made. A 10" disk of Pyrex 1.75 inches thick was cut with six pockets of various kinds as shown in Fig. I. The two at the lower right were done first to gain experience. They show considerable residual strain, indicating that the cutting had been too fast. The feed and force were changed then with the very favorable result in the pair at the upper left. Here the wall was reduced to about 0.060". The holes are 1.25 inches deep. The polariscope shows no detectable strain in the closeup photograph Fig. II. With the preferred operating conditions, glass could be removed at about 0.9 cubic inches per hour. It seems quite reasonable that a useful mirror could be made by this method, but we have chosen to drop the method for several reasons.

Unsolved Problems

First, a diamond-ground glass surface can be made very smooth and attractive, but we have almost certainly paid a price: the ground

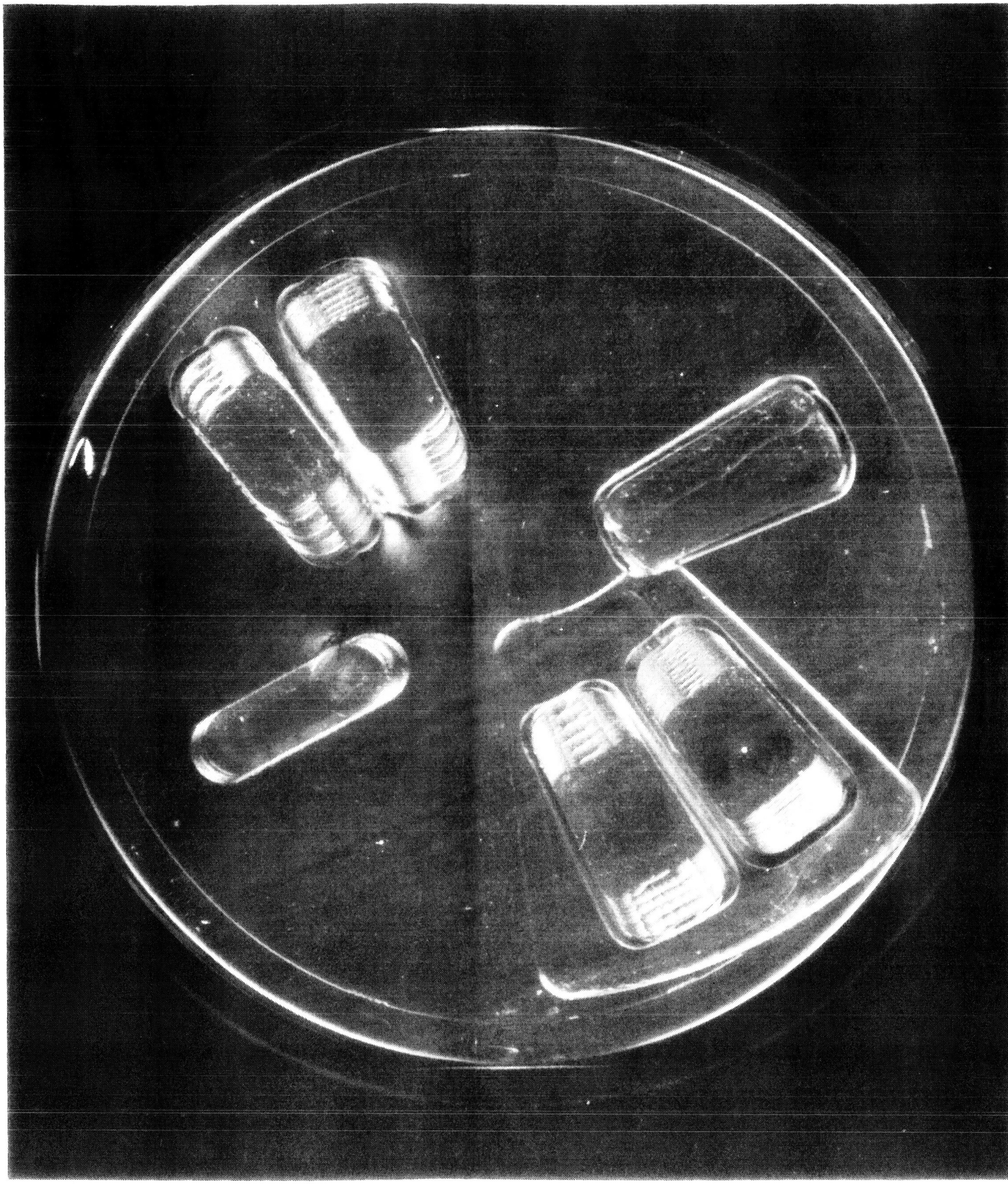

Fig. I. 10" Dia Pyrex Blank with a Series of Trial Pockets as seen in Polariscope

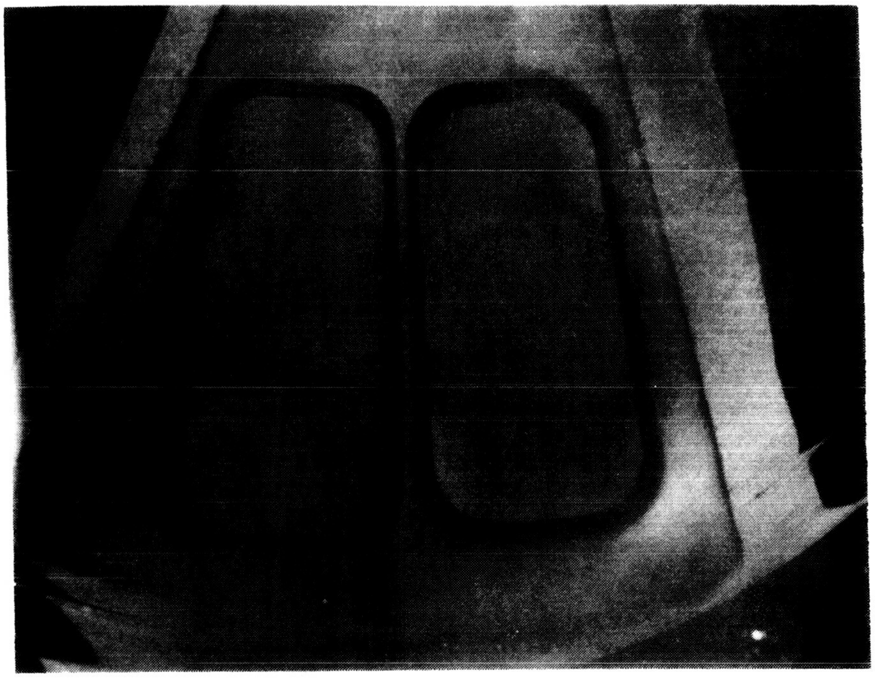

Fig. II. A .06" thick filleted wall as seen in a polariscope

With the top of the wall polished, the walls appear only slightly bi-concave and quite free from strain.

Photograph is .83 of full size

surface left by the diamond tool abounds in faults and is swollen by cracks to strain the interior volume of the thin walls[1]. The straining of a body by a ground surface was first noticed in 1905 by Twyman[2] and is called the Twyman effect. This effect, which can actually increase the area of a ground surface, puts glass in tension when it lies between two ground surfaces as it does in our experiments. It probably sets the limit to which a surface may be thinned, and reduces the breaking strength. It also probably introduces inelasticity. The problem of fissures and stress alleviation in ceramics is discussed by Kingery[3]. A possible solution is to work in an acid environment, or later to subject the part to an acid etch, but unless we solve this problem it seems probable that we have introduced a factor reducing the stability of the glass and weakening it.

Second, a good light weight structure probably needs a back-plate, and thus cannot be made entirely by grind milling, so some fusing will have to be done. If so, there is a question of just how much fusing should be done. It may be unwise to mix up the two methods.

Third, the technique makes an extremely heavy demand upon a skilled workman. We had hoped that the final operating method might be by a programed milling machine converted for the purpose. Then the work could be done at a slow rate but continuously. Numerous examples of digital milling in the aircraft industry indicate that the grind-milling of mirrors could be similarly automated where the space, capital investment, and experience existed.

Fourth, the size of a mirror is determined by the size of the blank and large mirrors would require very large volumes of material. Other methods employing built up sections do not reach this limit of

volume as soon, and the manufacturing methods for glass and quartz are volume-limited. For the above reasons the grind-milling technique has been laid aside.

References

1. M. Hetenyi, Handbook of Experimental Stress Analysis, Wiley, Inc. p. 894
2. F. Twyman, Prism and Lens Making, Hilger-Watts, p. 318
3. W. D. Kingery, Introduction to Ceramics, Wiley, p. 613

Acknowledgements

The help of Mr. P. Hauser throughout this work is gratefully acknowledged.